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Effects of new urban greenways on transportation energy use and greenhouse gas emissions: A longitudinal study from Vancouver, Canada

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1. Introduction

Urgent action on global climate change is necessary to avoid its most dangerous effects on human settlements and natural ecosystems within the next century. Multiple levels of government are now collectively addressing anthropogenic causes of climate change, including setting targets and actions for reducing greenhouse gas (GHG) emissions (Rogelj et al., 2016). In Canada, passenger road transportation accounts for 19% of all GHG emissions, with a continuing trend of rising emissions from increasing total vehicle-kilometers travelled (VKT) and the number of motor vehicles (Environment Canada, 2016). Major transportation decisions made at the local and regional levels will need to prioritize strategies that most effectively reduce GHG emissions (Baynham and Stevens, 2014; Yang et al., 2015). Investments in active transportation infrastructure are considered an important way to reduce motor vehicle use, and subsequently motorized energy use and emissions (Frank et al., 2010).

However, meaningful progress on climate change action has been difficult to achieve, in part due to the political infeasibility of the rapid changes needed to retrofit existing communities to be more energy efficient and less auto-dependent (Senbel and Church, 2011). For example, the implementation of active transportation improvement projects, such as protected bicycle lanes (or cycle tracks), have proven to be controversial among the general public (Siemiatycki et al., 2016). Reallocation of existing road space for other road users is perceived by many motorists as a "war on the car" despite established evidence of benefits for all road users (Cairns et al., 2002). In light of these barriers, coupled with the imperative of climate action, where should planning and transportation practitioners prioritize their efforts in order to maximize progress towards more environmentally sustainable development?

Research has long documented positive and statistically significant associations between built environment features and travel behavior (Ewing and Cervero, 2010; Frank et al., 2006). However, these conclusions are generally arrived at through the use of cross-sectional studies. The absence of controlled, longitudinal studies in the travel behavior literature makes it difficult to assess causal relationships of new transportation infrastructure on VKT reductions, and subsequently, energy use and GHG emissions. Researchers have made calls to expand the literature to include more evaluation studies of the built environment to provide causal evidence (Boarnet, 2011; Handy, 2017). Moreover, the adoption of longitudinal methods provides the additional benefit of addressing the residential self-selection issue in transportation research, where observed travel behavior is not only a function of people's residential built environment, but their attitudinal predispositions towards certain travel modes (Mokhtarian and Cao, 2008). For practitioners, causal evidence will help prioritize and better guide sustainable transportation policy and decision-making.

There exists a limited number of longitudinal studies evaluating the effects of active transportation infrastructure on travel behavior (Goodman et al., 2013, 2014; Hunter et al., 2015; Pucher et al., 2010; Yang et al., 2010). Even fewer studies evaluate the specific effect on motorized travel behavior and the impact on energy use and GHG emissions (Brand et al., 2014; Zahabi et al., 2016),

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with these studies only investigating the overall effect of multiple improvement projects or entire cycling networks. To address this gap in the literature, we present the results of a longitudinal case study of a single urban greenway.

Urban greenways are landscaped and traffic-calmed pathways with a mix of bicycle facilities and other streetscape improvements that link open spaces, parks, public facilities, and neighborhood centers together. Greenways support a variety of active travel uses, including walking, running, bicycling, and skating (Krizek et al., 2007; Lindsey, 1999). These types of multi-use facilities are preferred by a greater diversity of potential bicycle users, particularly women and adults with children (Winters and Teschke, 2010). Installing greenways have been found to improve perceptions among residents that their neighborhood environment is more favorable towards non-motorized travel (Ma and Dill, 2015). As a result, the provision of greenways is hypothesized to be an effective strategy to reduce motor vehicle use among the general population. However, existing research on greenways focus exclusively on the effects on active travel behavior (Evenson et al., 2005; Fitzhugh et al., 2010; Merom et al., 2003; West and Shores, 2011), with no formal evaluation on motor vehicle use and changes in VKT.

The aim of this paper is to evaluate the effect of an urban greenway on motorized travel behavior. This paper uses data from the Comox-Helmcken Greenway Study, a three-year study led by Dr. Lawrence Frank that took place from 2012 to 2015 investigating the impacts of the Comox-Helmcken Greenway (Comox Greenway) in Vancouver, Canada before and after its construction. We make two novel contributions to the literature—this is the among the first quasi-experimental, longitudinal cohort study of the travel behavior effects of active transportation infrastructure, and likely the first reported study of the effect of an urban greenway on energy use and GHG emissions. For the present study, we ask the following question: what was the effect of the Comox Greenway on transportation energy use and GHG emissions for residents living near the greenway before and after its construction?

2. Methods

2.1. Study area

The study area is in the West End neighborhood of downtown Vancouver. The West End is a high-density, mixed residential and commercial neighborhood, and is considered to be one of the most compact and non-auto-dependent neighborhoods in the Vancouver region (Frank et al., 2010).

This study evaluates the Comox Greenway, a major active transportation corridor extending west-to-east from Stanley Park through downtown Vancouver between Stanley Park Lane and Hornby Street. The greenway was designed to be comfortable and safe for users of all ages and abilities, providing a new route in the downtown bicycle network for both utilitarian commuters and recreational riders. Fig. 1 shows the changes along the Comox Greenway. The two-kilometer long corridor consists of a mix of cycling facility improvements: one-way shared on-street with counterflow lanes (22%); one-way protected (29%); and two-way shared on-street (49%). Other improvements included: (1) new and upgraded traffic signals; (2) new street paving, concrete medians and curb bulges, catch basins, paint, and signage; (3) new sidewalks, curb ramps, and raised crosswalks; (4) new and upgraded street, sidewalk, and park lighting; and (5) new public realm amenities, such as seating, planting, trees, drinking fountains, and wayfinding features.

2.2. Sampling procedure

The Comox-Helmcken Greenway Study is a natural experiment that tracked a cohort of residents during two waves of longitudinal samples. A random sample of household addresses were identified by Mustel Group, a third-party market research company, using the Canada Post address data file as the sampling frame. Invitation letters were sent out by mail by the City of Vancouver to potential participants. Residents were recruited into the study if they were living approximately within a kilometer of the Comox Greenway in Vancouver and had no plans to move outside the study area during the time of the study. Reference to the Comox Greenway was not specified to minimize participation bias.

A survey was conducted during the fall and winter for both before-and-after periods with a two-year follow-up period (time 1 baseline: October 2012 – March 2013; time 2 follow-up: October 2014 – March 2015); the greenway completed construction and opened in June 2013. Participants completed an online two-day personal travel survey and a detailed questionnaire with a hardcopy back-up available. Incentives for participation included gift certificates and a prize draw to civic facilities ($10 and $1,000 value respectively). A total of 1,744 mailings were sent out. For the baseline period, a total of 1,113 participants were recruited (63.82% response rate).

Participants were excluded from the study if they did not participate in the follow-up period ($n = 556$), did not complete the survey for the two survey days ($n = 25$), or were otherwise ineligible ($n = 8$). The final sample size for analysis was 524 participants (30.1% response rate; 47.1% attrition rate).

For the present study, the sample was assigned to two groups based on residential proximity from the greenway in order to estimate the intervention exposure: 239 participants in the treatment group living within 300 m of the Comox Greenway, and 285 participants in the control group living further than 300 m (see Fig. 2). The use of proximity to define the treatment condition is similar to previous longitudinal research (West and Shores, 2011, 2015). The base threshold of 300 m in this study was selected based on a qualitative assessment. First, 300 m is equal to two-and-a-half street blocks using the existing street grid in the study area before reaching a major commercial street (Davie Street). Beyond this distance, residents have the option of choosing a more attractive off-road shared pedestrian and cyclist pathway along the waterfront (Seaside Greenway); this type of facility has been identified as the most preferred route type among current and potential cyclists (Winters and Teschke, 2010). Second, 300 m provides a roughly equal

Fig. 1. Photos of the West End neighborhood before and after the Comox-Helmcken Greenway.
Source: City of Vancouver and Paul Krueger (photos A to C), Google Street View (photo D: before), Ken Ohrn (photo D: after)

sample size for the treatment and control groups to ensure valid comparison. What constitutes an appropriate distance threshold for quasi-experimental studies of this nature is not well established in the built environment and travel behavior literature (Boarnet, 2011). To address this theoretical gap, a sensitivity analysis was conducted for participants living 100, 200, 400, and 500 m and more from the greenway.

Fig. 2. The Comox Greenway study area with the locations of participants' primary place of residence.

2.3. Measures

2.3.1. Socio-demographic data

Participants completed a self-report questionnaire with questions on demographic characteristics, vehicle ownership, and travel mode preferences. Demographic variables included age; gender (1 = male); ethnicity (1 = white); employment status (1 = employed full- or part-time); total annual household income (1 = "less than $10,000"; 2 = "$10,000–$19,999"; 3 = "$20,000–$29,999"; 4 = "$30,000–$39,999"; 5 = "40,000–$59,999"; 6 = "60,000–$79,999"; 7 = "$80,000–$99,999"; 8 = "more than $100,000); and the total number of household residents. Dummy variables were used for motor vehicle and bicycle ownership. A dummy variable for car sharing membership was included to account for the significant growth of car sharing services in the study area during the study period (Namazu and Dowlatabadi, 2018). Travel mode preference variables for driving and public transit were ranked on an ordinal scale from 1 to 4, where 1 was the least preferred, and 4 was the most preferred.

2.3.2. Travel survey data

Participants completed a self-report two-day personal travel survey, containing data on origin–destination (O–D), trip purpose, route, and mode of travel.

Participants were randomly assigned two days of the week to complete their travel survey in order to ensure an equal distribution of days and to capture both weekday and weekend travel. For each recorded trip, the origin and destination were geocoded in ArcGIS (version 10.1) based on the exact street address when provided or the center of the closest street intersection. ArcGIS Network Analyst was then used to estimate the distance travelled for each trip using a shortest path assignment and self-reported information to determine the route. For the present study, only motor vehicle and transit bus trips (taxi trips were combined with vehicle trips) were included in the scope of analysis in order to estimate the effects on the motorized energy and emission outcomes. We focused the analysis on utilitarian trips following Zahabi et al. (2016), as these types of trips generate the greatest environmental externalities and their travel characteristics are generally stable over time. The travel survey covered six utilitarian trip purposes: work, education, personal business, shopping, dining, and passenger pick-up/drop-off. In order to isolate the local effects of the greenway, the analysis only included trips that took place entirely within the Vancouver region and had an origin and/or destination within downtown Vancouver.

Participants were re-recruited during the same time of year in order to match seasonal conditions. As weather conditions can impact travel, temperature and precipitation data were retrieved from an Environment Canada weather monitoring station to control for varying conditions during the baseline and follow-up period (Saneinejad et al., 2012). Daily temperature and precipitation data were averaged over the two diary days, with the precipitation variable dichotomized into a dummy variable (1 = greater than or equal to 3 mm). The cut-off of 3 mm was determined using the 75% percentile (rounded down) based on the assumption that a very modest amount of precipitation would not affect travel behavior in order to reflect the study area context.

2.3.3. Energy use and GHG emission data

Energy use and GHG emissions were estimated using intensity factors applied to the estimated travel distance generated from the O–D data. Energy and emissions factors are based on provincial standards for quantifying community-wide GHG emissions in British Columbia as described in the 2010 Community Energy and Emissions Inventory (CEEI) (BC Ministry of Environment, 2017).

Vancouver-specific intensity factors for passenger vehicles were developed based on registered vehicles in the city obtained from the CEEI. Weighted average fuel efficiency for passenger vehicles was 11.8 L/100 km, with weighted average energy and emissions intensity of (hybrid) gasoline and diesel fuels of 34.7214 MJ/L and 2.3362 kg CO_2e/L. The resulting passenger vehicle energy and emissions intensity factors were 4.0912 MJ/VKT and 0.2609 kg CO_2e/VKT. Per-trip energy expenditure and GHG emissions for passenger vehicle trips were calculated by multiplying the energy and emissions factors by the vehicle travel distance, and then dividing by the number of reported vehicle occupants. Energy and emissions factors per PKT (passenger-kilometer travelled) for city buses in Vancouver were taken from the CEEI as 0.7460 MJ/PKT and 0.0904 kg of CO_2e/PKT.[1] Per-trip energy expenditure and GHG emissions for bus trips were calculated by multiplying the energy and emissions factors by the bus travel distance.

Trip-level energy and emissions were aggregated at the individual level to calculate the two dependent variables, average daily GHG emissions (kg of CO_2e/day) and energy use (MJ/day).

2.4. Statistical analysis

The study used the difference in differences approach to estimate the intervention effect of the greenway. Linear mixed effect regression models were fitted with a random intercept for subjects using the xtmixed procedure in Stata (version 12), where the dependent variables (average daily GHG emissions and energy use) were regressed with the GROUP variable (1 = treatment group), TIME (1 = baseline; 2 = follow-up), and an interaction term, GROUP × TIME. The use of an interaction term allows the model to estimate the dependent variables' change over time from an intervention relative to the control group (Twisk, 2013). Four models were estimated: model 1 (unadjusted), model 2 (socio-demographic covariates), model 3 (travel preference covariates), and the final adjusted model 4 (weather covariates). The analysis used a restricted sample ($N = 477$) due to item nonresponse for the household income variable (Ting et al., 2010). The direction of the unadjusted model parameters remained robust between the restricted and unrestricted sample, and the estimated parameters were also within range in the adjusted model with and without the inclusion of the income covariate. Eq. (1) shows the form of the regression:

$$Y_{ij} = \beta_0 + b_{0i} + \beta_1 T_i + \beta_2 t_{ij} + \beta_3 (T_i \times t_{ij}) + \gamma' X'_{ij} + e_{ij} \tag{1}$$

where

i: subject
j: time
Y_{ij}: average daily energy or emission for subject i at time period j
β_0: overall intercept across all subjects
b_{0i}: random intercept for subject i
T_i: GROUP dummy variable
t_{ij}: TIME dummy variable
$T_i \times t_{ij}$: interaction term between GROUP and TIME
X'_{ij}: vector of covariates
$\beta_1, \beta_2, \beta_3, \gamma'$: estimated parameters ($\gamma'$ is a vector of fixed effects)
e_{ij}: error term.

Repeated measure (paired) *t*-tests were conducted for all the variables between the baseline and follow-up. Two-tailed *t*-tests were conducted cross-sectionally during the baseline to compare the treatment and control group.

[1] The energy and emissions intensity factors used for city buses were based on data from the regional transportation authority (TransLink). The factors applied to Vancouver assumed a bus occupancy of 29 passengers. This produced a load of 35% to 38% for a typical trolley bus (maximum capacity of 77 to 82 passengers), and a load of 121% for a community shuttle (maximum capacity of 24 passengers).

Table 1
Sample characteristics.

	Time	Treatment (n = 239)		Control (n = 285)	
		Mean or %	SD	Mean or %	SD
Age	1	46.20	14.74	44.68	14.49
	2	48.23***	14.72	46.66***	14.48
Gender (% Male)	1 & 2	44.77%	49.83%	41.05%	49.28%
Ethnicity (% White)**	1 & 2	88.70%	31.72%	80.35%	39.80%
Employment status (%)	1	72.80%	44.59%	76.84%	42.26%
	2	72.80%	44.59%	76.49%	42.48%
Household income (%)					
< $10,000	1	2.31%	15.07%	0.78%	8.79%
	2	0.46%*	0.68%	1.54%	12.35%
$10,000–$19,999	1	6.02%	23.83%	5.81%	23.40%
	2	6.45%	24.62%	4.63%	21.06%
$20,000–$29,999	1	9.72%	29.69%	5.81%	23.40%
	2	7.83%	26.93%	8.10%	27.35%
$30,000–$39,999	1	9.72%	29.69%	13.19%	33.89%
	2	10.13%	30.25%	8.10%*	27.35%
$40,000–$59,999	1	22.69%	41.98%	22.09%	41.57%
	2	20.28%	41.30%	18.91%	39.24%
$60,000–$79,999	1	17.13%	37.76%	18.22%	38.67%
	2	18.89%	39.24%	19.30%	39.54%
$80,000–$99,999	1	12.50%	33.15%	14.34%	35.12%
	2	13.36%	34.11%	11.20%	31.59%
> $100,000	1	19.91%	40.02%	19.77%	39.90%
	2	22.58%	41.91%	28.19%***	45.07%
Number of household residents	1	1.60	0.71	1.53	0.74
	2	1.62	0.76	1.58*	0.75
Motor vehicle ownership (%)	1	43.09%	49.63%	49.12%	50.08%
	2	46.03%	49.95%	49.35%	50.08%
Bicycle ownership (%)	1	54.39%	49.91%	58.60%	49.34%
	2	59.00%*	49.29%	59.74%	49.12%
Car sharing membership (%)	1	24.27%	42.96%	19.30%	39.53%
	2	30.96%***	46.33%	27.60%***	44.77%
Motor vehicle preference	1	2.19	1.02	2.16	0.95
	2	2.32*	0.98	2.23	0.96
Public transit preference	1	2.41	0.87	2.36	0.88
	2	2.29*	0.91	2.35	0.92

Note: Significance for paired t-test reported for time 1 baseline and time 2 follow-up (asterisks indicated in time 2 row) and treatment and control during time 1 baseline (asterisks indicated beside variable).
$p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

3. Results and discussion

3.1. Sample characteristics

Table 1 reports descriptive statistics for the sample. During the baseline, the age of the overall sample ranged from 21 to 90 years, with a median age of 44 years in the treatment and 43 years in the control. The majority of the sample identified as female, with 53.23% in the treatment and 58.95% in the control. There were no significant differences between the treatment and control with the exception of ethnicity (88.70% white in the treatment and 80.35% in the control, $p = 0.009$). Bicycle ownership increased in the treatment with a percentage change of 8.48% ($p = 0.028$). The greatest increase was for car sharing membership, with a percentage change of 27.56% in the treatment ($p < 0.001$) and 43.01% in the control ($p = 0.001$).

3.2. Transportation characteristics

Table 2 reports the results for changes in travel distance, GHG emissions, and energy use. In percentage terms, motorized travel distance decreased in the treatment by 17.70% from 3.39 km/day in the baseline to 2.79 km/day in the follow-up. This effect was observed despite a modest non-significant increase in motor vehicle ownership and a significant increase in car sharing membership after the greenway (see Table 1). GHG emissions and energy use generally had a commensurate reduction, but the changes were not significant (20.9% reduction from 0.66 kg CO_2e/day to 0.52 kg CO_2e/day, $p = 0.065$; 21.35% reduction from 9.25 MJ/day to 7.27 MJ/day, $p = 0.070$).

In contrast to the treatment, travel distance in the control increased by 36.68% from 1.88 km to 2.58 km. While motor vehicle ownership did not change for the control after the greenway, there was a significant increase in car sharing membership, which may have contributed to the total increase in travel distance. Correspondingly, significant increases for both GHG emissions and energy

Table 2
Transportation characteristics: GHG emissions, energy use, and travel distance.

	Time	Treatment (n = 239)		Control (n = 285)	
		Mean or %	SD	Mean or %	SD
Average motorized travel distance (km/day)***	1	3.39	5.96	1.88	3.19
	2	2.79	5.67	2.58*	5.68
Average GHG emissions (kg CO_2e/day)***	1	0.66	1.41	0.33	0.64
	2	0.52	1.23	0.51*	1.44
Average energy use (MJ/day)***	1	9.25	20.93	4.43	9.31
	2	7.27	18.17	7.20*	21.39

Note: Significance for paired t-test reported for time 1 baseline and time 2 follow-up (asterisks indicated in time 2 row) and treatment and control during time 1 baseline (asterisks indicated beside variable).
$p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

use were observed in the control (57.70% increase from 0.33 kg CO_2e/day to 0.51 kg CO_2e/day, $p = 0.031$; 62.88% increase from 4.43 MJ/day to 7.21 MJ/day, $p = 0.031$).

3.3. GHG emissions and energy use model results

Table 3 shows the model results for GHG emissions and Table 4 shows the model results for energy use. As GHG emissions and energy use were calculated using proportional intensity factors, only the results for the emissions model are discussed below for sake of brevity as the coefficients are similar. To evaluate the effect of the Comox Greenway on emissions and energy, attention is given to the interpretation of the interaction term.

In model 1, emissions in the control significantly increased by 0.32 kg CO_2e/day ($p = 0.003$). However, the interaction term between group and time was negatively associated with emissions ($p = 0.002$), indicating that there was a statistically significant difference in the change from baseline to follow-up depending on whether subjects were in the treatment or control: a −0.37 kg CO_2e/day reduction effect of the Comox Greenway. Models 2 to 4 show the stepwise effect of adding covariates, with coefficient directions remaining stable throughout the three models.

For the final adjusted model, we found that the Comox Greenway reduced GHG emissions in the treatment by −0.40 kg CO_2e/day ($p = 0.001$). Employment status, vehicle ownership, and motor vehicle travel preference were found to have significant positive associations with emissions ($p = 0.011$; $p < 0.000$; and $p < 0.001$ respectively). These factors are consistent with mode choice models in the literature; people who are employed, own a vehicle, and have a preference for driving are more likely to drive more,

Table 3
Linear mixed effects models of transportation-related GHG emissions.

	Model 1			Model 2			Model 3			Model 4		
	β	SE	p	β	SE	p	β	SE	p	β	SE	p
Greenway												
Group (1 = Treatment)	0.32**	0.11	0.003	0.37**	0.10	0.000	0.35**	0.10	0.001	0.35**	0.10	0.001
Time (2 = Follow − up)	0.22**	0.08	0.008	0.22**	0.08	0.009	0.21*	0.08	0.013	0.20*	0.09	0.029
Group × Time	−0.37**	0.12	0.002	−0.39**	0.12	0.001	−0.40**	0.12	0.001	−0.40**	0.12	0.001
Socio-demographic												
Age				−0.00	0.00	0.459	−0.00	0.00	0.406	0.00	0.00	0.405
Gender (1 = Male)				−0.05	0.08	0.572	−0.03	0.08	0.758	−0.02	0.08	0.767
Ethnicity (1 = White)				0.07	0.12	0.588	0.09	0.12	0.435	0.09	0.12	0.469
Employment (1 = Employed)				0.30**	0.11	0.007	0.28*	0.11	0.011	0.28*	0.11	0.011
Household income (1 = < $10,000; 8 = $100,000+)				−0.03	0.03	0.330	−0.03	0.03	0.274	−0.03	0.03	0.283
Number of household residents				0.05	0.06	0.438	0.06	0.06	0.292	0.06	0.06	0.298
Motor vehicle ownership (1 = Yes)				0.71***	0.09	0.000	0.58***	0.09	0.000	0.58***	0.09	0.000
Bicycle ownership (1 = Yes)				−0.08	0.09	0.363	−0.02	0.09	0.824	−0.02	0.09	0.831
Car sharing membership (1 = Yes)				0.06	0.10	0.526	0.06	0.10	0.555	0.06	0.10	0.541
Travel												
Motor vehicle preference (4 = most preferred)							0.17***	0.05	0.000	0.17***	0.05	0.000
Public transit preference (4 = most preferred)							−0.01	0.05	0.837	−0.01	0.05	0.826
Weather												
Average daily temperature (°C)										−0.01	0.02	0.634
Average daily precipitation (1 = ≥ 3 mm)										−0.03	0.08	0.680
Constant	0.31	0.07	0.000	−0.08	0.26	0.764	−0.40	0.33	0.215	−0.03	0.35	0.376
N	477			477			477			477		

Note: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

Table 4
Linear mixed effects models of transportation-related energy use.

	Model 1			Model 2			Model 3			Model 4		
	β	SE	p	β	SE	p	β	SE	p	β	SE	p
Greenway												
Group (1 = Treatment)	4.78**	1.62	0.003	5.52**	1.54	0.000	5.25**	1.52	0.001	5.30***	1.52	0.000
Time (2 = Follow − up)	3.25*	1.22	0.008	3.21*	1.23	0.009	3.09*	1.24	0.013	2.84*	1.33	0.033
Group × Time	−5.51**	1.80	0.002	−5.84**	1.81	0.001	−5.99**	1.82	0.001	−5.97**	1.82	0.001
Socio-demographic												
Age				−0.03	0.05	0.514	−0.04	0.05	0.461	−0.04	0.05	0.463
Gender (1 = Male)				−0.78	1.25	0.528	−0.44	1.22	0.719	−0.42	1.22	0.729
Ethnicity (1 = White)				0.99	1.78	0.579	1.39	1.74	0.425	1.30	1.75	0.457
Employment (1 = Employed)				4.25**	1.62	0.009	3.92*	1.60	0.014	3.90*	1.60	0.015
Household Income (1 = < \$10,000; 8 = \$100,000 +)				−0.32	0.38	0.408	−0.36	0.38	0.335	−0.36	0.38	0.344
Number of Household Residents				0.77	0.90	0.456	0.92	0.88	0.299	0.90	0.88	0.304
Motor Vehicle Ownership (1 = Yes)				10.85***	1.31	0.000	8.89***	1.37	0.000	8.85***	1.37	0.000
Bicycle Ownership (1 = Yes)				−1.14	1.28	0.370	−0.32	1.34	0.812	−0.30	1.34	0.820
Car sharing Membership (1 = Yes)				0.73	1.42	0.606	0.63	1.40	0.652	0.66	1.40	0.636
Travel												
Motor Vehicle Preference (4 = most preferred)							2.61***	0.68	0.000	2.63***	0.68	0.000
Public Transit Preference (4 = most preferred)							−0.31	0.74	0.679	−0.32	0.74	0.668
Weather												
Average Daily Temperature (°C)										−0.13	0.28	0.648
Average Daily Precipitation (1 = ≥ 3 mm)										−0.70	1.23	0.568
Constant	4.15	1.09	0.000	−2.07	3.81	0.655	−6.64	4.85	0.171	−5.16	5.24	0.325
N	477			477			477			477		

Note: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

and subsequently emit more GHG emissions (Schneider, 2013). Participants who owned a vehicle emitted an average of 0.58 CO_2e/day more than those who did not own a vehicle when holding all other variables constant. The finding of a reduction effect of the greenway remained robust with and without the addition of covariates in the model.

The direction and magnitude of the coefficients for the emissions model are similar to the energy use model, in which the Comox Greenway treatment effect was estimated as a −5.97 MJ/day reduction in transportation energy use ($p = 0.001$).

3.4. Sensitivity testing

Sensitivity analysis was conducted to assess the effect of residential proximity from the greenway on the GHG emissions and energy outcomes. The regression models were estimated for GHG emissions and energy at five distance thresholds from 100 to 500 m

Table 5
Sensitivity testing of transportation-related GHG emissions and energy use models with different distance thresholds.

	100 m			200 m			300 m			400 m			500 m		
	β	SE	p	β	SE	p	β	SE	p	β	SE	p	β	SE	p
GHG emission															
Group (1 = Treatment)	0.18	0.16	0.275	0.22	0.11	0.052	0.35**	0.10	0.001	0.29*	0.11	0.012	0.40*	0.16	0.011
Time (2 = Follow − up)	0.04	0.07	0.570	0.11	0.08	0.167	0.20*	0.09	0.029	0.12	0.12	0.327	0.27	0.18	0.140
Group × Time	−0.26	0.20	0.193	−0.33*	0.13	0.014	−0.40**	0.12	0.001	−0.16	0.14	0.251	−0.29	0.19	0.121
n (Treatment)	59			158			239			366			452		
n (Control)	465			366			285			158			72		
Energy use															
Group (1 = Treatment)	2.89	2.43	0.235	3.38*	1.66	0.042	5.30***	1.52	0.000	4.40**	1.68	0.009	6.05*	2.33	0.009
Time (2 = Follow − up)	0.53	1.09	0.627	1.60	1.20	0.179	2.84*	1.33	0.033	1.67	1.78	0.347	4.05	2.67	0.130
Group × Time	−3.77	2.93	0.198	−5.03*	1.20	0.012	−5.97**	1.82	0.001	−2.34	2.02	0.246	−4.51	2.77	0.104
n (Treatment)	59			158			239			366			452		
n (Control)	465			366			285			158			72		

Note: Covariates in adjusted model: age, gender (1 = male), ethnicity (1 = white), employment status (1 = employed full- or part-time), total annual household income (1 = "less than \$10,000"; 2 = "\$10,000 – \$19,999"; 3 = "\$20,000 – \$29,999"; 4 = "\$30,000 – \$39,999"; 5 = "40,000 – \$59,999"; 6 = "60,000 – \$79,999"; 7 = "\$80,000 – \$99,999"; 8 = "more than \$100,000), total number of household residents, motor vehicle ownership, bicycle ownership, car sharing membership, travel mode preference for driving and public transit (1 = least preferred; 4 = most preferred), mean temperature (°C), and precipitation (≥ 3 mm).
$p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***).

using 100 m intervals (see Table 5; only the results of the final adjusted model are presented). Interpretation is focused on the interaction term.

For participants living 100 m away, the greenway was associated with a reduction of −0.26 kg CO2e/day and −3.77 MJ/day. This effect increased in magnitude at 200 m (−0.33 kg CO2e/day and −5.03 MJ/day) before reaching an upper limit at 300 m (−0.40 kg CO2e/day and −5.97 MJ/day). At 400 and 500 m, the estimated effect of the greenway diminished in magnitude and was generally lower than the effect sizes observed at 200 to 300 m. The models were only statistically at the 200- and 300-meter distance intervals. However, the difference in significance levels is partially due to the imbalanced number of observations in the treatment and control group at the more extreme distance thresholds.

4. Discussion and conclusions

This paper assesses the causal relationship between an urban greenway, motorized travel behavior, and environment outcomes, and provides the first quantification in the literature of the effect of a greenway on transportation-related GHG emissions and energy use. For residents living near the Comox Greenway, their daily transportation GHG emissions decreased by 20.90% after the greenway's construction. Adjusting for covariates and the control group, the greenway was associated with a significant reduction of −0.40 kg CO_2e/day and −5.30 MJ/day ($p = 0.001$). The change in emissions was attributed to a reduction in VKT, enabled through the provision of high-quality active transportation infrastructure through cycling facilities and other streetscape improvements. Our sensitivity analysis results indicated that the effects of the greenway differed by proximity. The emission reduction associated with the greenway increased with distance, gradually from 100 to 200 m before reaching an upper limit at 300 m.

This study is one of the few longitudinal studies investigating the relationship between active transportation infrastructure and motorized travel behavior. Our findings help advance the travel behavior literature in several ways. First, using a quasi-experimental design, we provide causal evidence that active transportation infrastructure improvements can lead to a desired reduction in motor vehicle use, resulting in a reduction in transportation-related GHG emissions and energy. Second, we demonstrate that the effects of the greenway are not uniform across space and instead differ by residential proximity. This point merits further investigation, as the literature currently lacks a standardized distance threshold for transportation infrastructure evaluation studies.

Earlier research used a variety of differing and inconsistent thresholds across multiple studies and built environment contexts (Hunter et al., 2015). An appropriate threshold will likely depend on the intervention under investigation and characteristics of participants such as age, with different pedestrian and bicycle facility types (e.g., an off-street path vs. a cycle track) generating a different 'catchment area'. Our findings suggest that future research will need to account for the role of proximity when evaluating the effect of active transportation facilities on travel-related outcomes to avoid potential underestimation. However, more investigation is needed on this point of research design. The use of a distance threshold may potentially oversimplify travel behavior change, as residents in the control may also be induced to change their travel patterns (Boarnet, 2011). And lastly, our study is one of the few longitudinal studies that account for weather patterns when studying the impacts of built environment features on travel behavior.

While this study offers some important contributions to the literature, several questions remain and more work is needed. Specifically, future longitudinal research on the Comox Greenway will need to explore the intermediate causal mechanisms on the observed travel outcomes. Did the treatment group reduce their motor vehicle travel, and subsequently energy and emissions, as a result of changing travel preferences from the construction of the greenway, or did the greenway make it more difficult for motor vehicle use, or was it a combination of the two? How much of a causal effect did the greenway have on promoting active forms of travel (e.g., walking and cycling) and the degree of mode substitution (i.e., motor vehicle users switching to walking and cycling)? How did prior behavior influence travel behavior after the greenway? Built environment interventions have been found to have differential effects depending on individuals' prior behavior and motivations (Gardner, 2009). For example, Hong et al. (2016) found that residents living proximate to a new light rail line increased their active travel, but this effect was greater for residents with less baseline physical activity prior to the light rail. And lastly, specific to our study context, did the proliferation of car sharing services during the study period dampen the results of the greenway? The control group results suggest that the greenway may have overcome what would have otherwise been a net increase in vehicle use. The use of the active travel mode data collected from the travel survey, advanced statistical models such as structural equation modelling (Cao et al., 2007; Golob, 2003), attitudinal surveys, and other research methods will help address these questions.

Our study has a few limitations. First, the GHG emissions and energy outcomes are estimated using shortest path assignment based on self-report data. The use of more objective data collection methods such as accelerometers and GPS is recommended in the future to better capture actual travel patterns. On the other hand, these methods can increase data collection costs, participant burden, and potential participation bias. One implication of shortest path assignment is that our analysis produces a conservative underestimation of transportation-related GHG emissions and energy as it assumes the shortest route travelled. This measurement bias would be present in both before-and-after time periods; as a result, it is not expected to affect the findings in a meaningful way. Second, our study has limited generalizability as the treatment effect attributed to the greenway in this study were found in a dense neighborhood with high street connectivity and generally good pedestrian infrastructure and transit options. Third, the analysis isolates the greenway with respect to the total bicycle network. In other words, a standalone greenway in an area with no other bicycle facilities may have a different effect than a new greenway within a fully developed network. As a result, our estimated treatment effect may also be capturing the effect of the total bicycle network on motor vehicle use in downtown Vancouver relative to the Comox Greenway. Lastly, the study did not explicitly model the effects of the various microscale streetscape features from the greenway improvement on VKT reductions. Capturing these changes through validated measurement tools (Clifton et al., 2007;

Millstein et al., 2013) would model the actual changes to the built environment after the greenway.

Ultimately, it is the intention of this study to help guide decision-making for transportation investments towards climate change mitigation. Our findings will help practitioners better understand what strategies they can pursue to achieve environmental sustainability goals and meet emission reduction targets in the transportation sector. More work is needed to understand the relative merits of other active transportation infrastructure on environmental outcomes. How do the benefits of the $5.46 million spent to construct the Comox Greenway compare with other possible active transportation interventions? Overall, a primary takeaway from our study is that emission reductions can still be made in high-density, compact neighborhoods with relatively low vehicle ownership through modest investments in active transportation facilities.

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